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Nakamura et al.

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(54) **INDUCTOR AND METHOD FOR FABRICATING THE SAME**

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(30) **Foreign Application Priority Data**

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H01F 7/06 (2006.01)

(52) **U.S. Cl.** **336/200**; 336/223; 336/232; 29/602.1

(58) **Field of Classification Search** 336/200, 336/223, 232; 29/602.1
See application file for complete search history.

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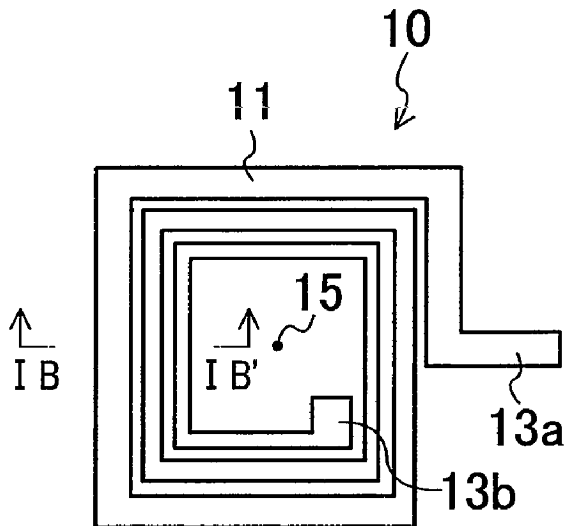
(57) **ABSTRACT**

An inductor includes a flat substrate and a conductor in a spiral shape having a plurality of turns. The plane on which the conductor is formed is substantially in parallel with a principal surface of the substrate. The turns of the conductor are equally spaced from each other in a direction parallel to the plane on which the conductor is formed. An outer one of the turns of the conductor is wider and thinner than an inner one of the turns of the conductor. A level of at least one of a top and a bottom of the conductor differs from one turn to another in a cross section vertical to the plane on which the conductor is formed.

12 Claims, 8 Drawing Sheets



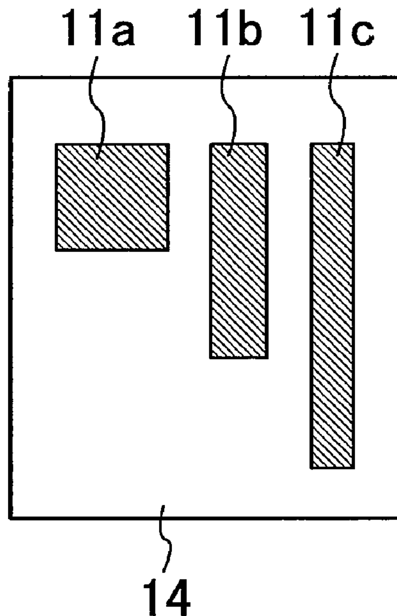


FIG.1A

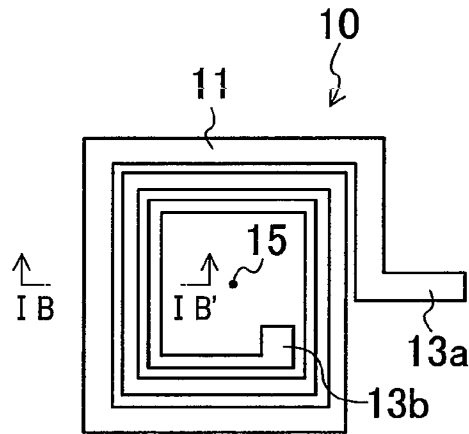


FIG.1B

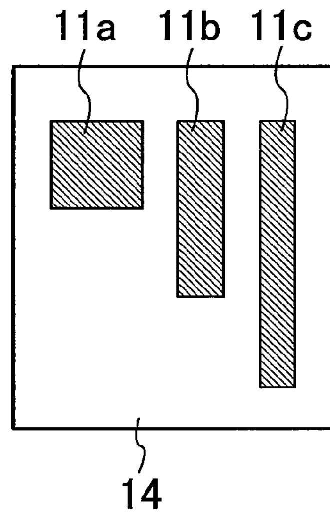


FIG.1C

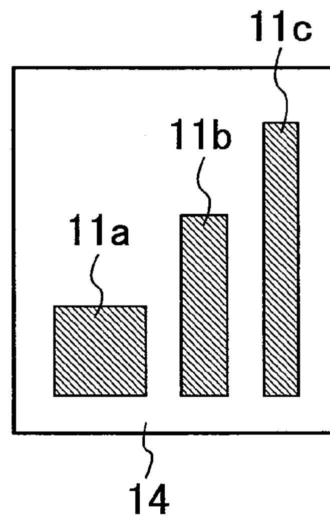


FIG.2A

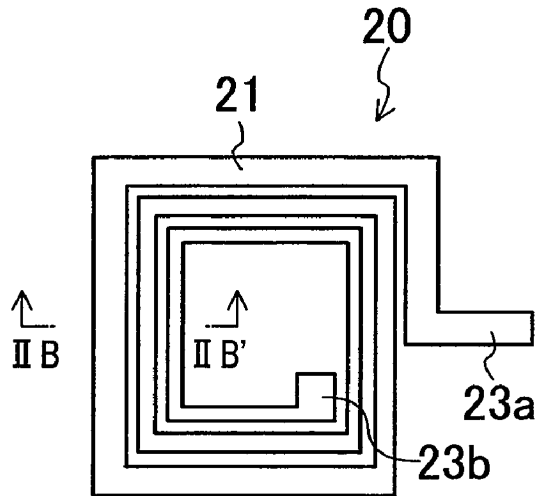


FIG.2B

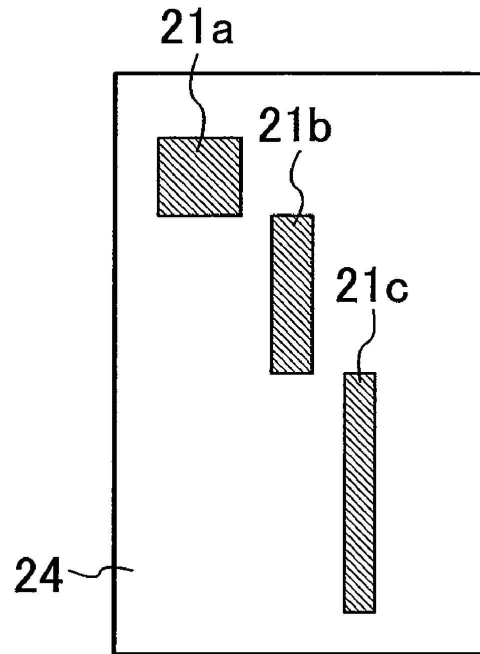


FIG.2C

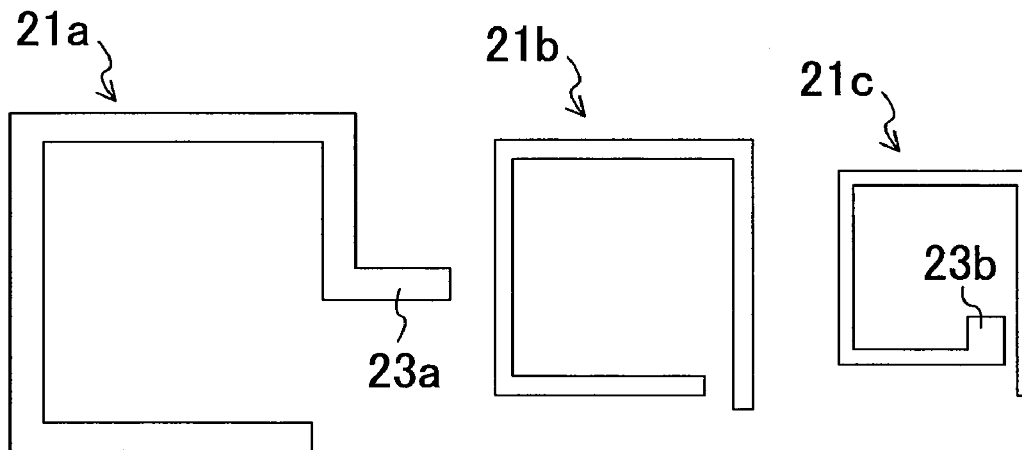


FIG.3A

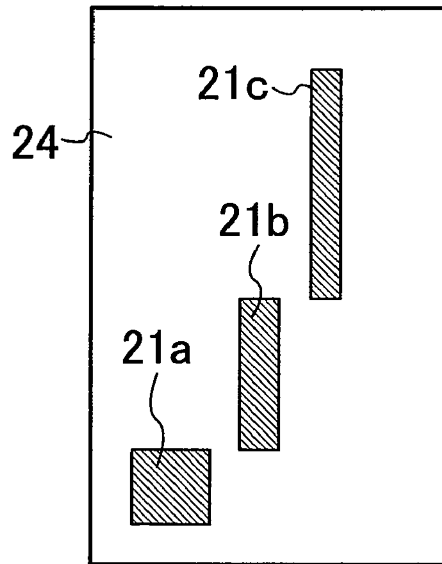


FIG.3B

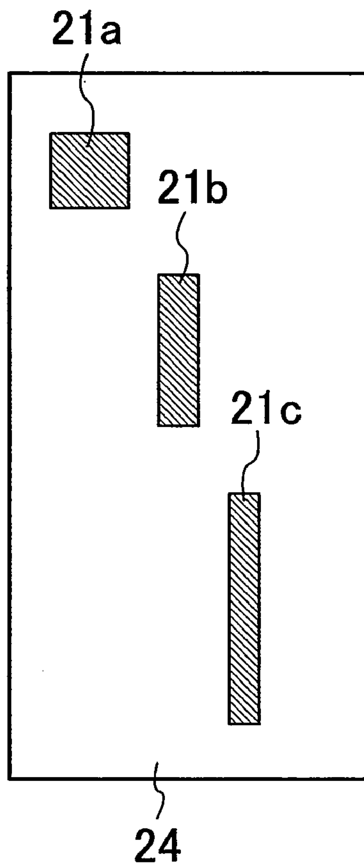


FIG.3C

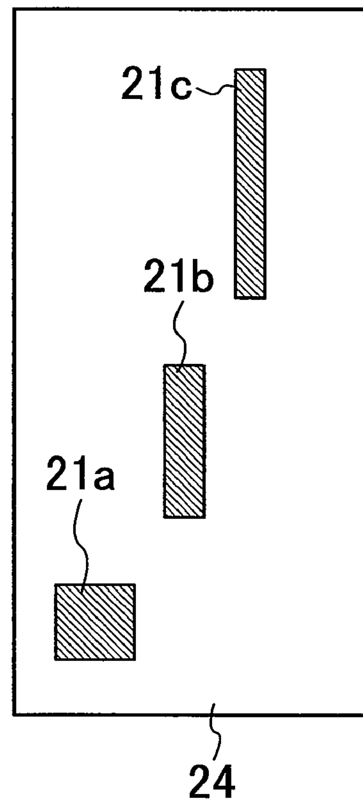


FIG.4A

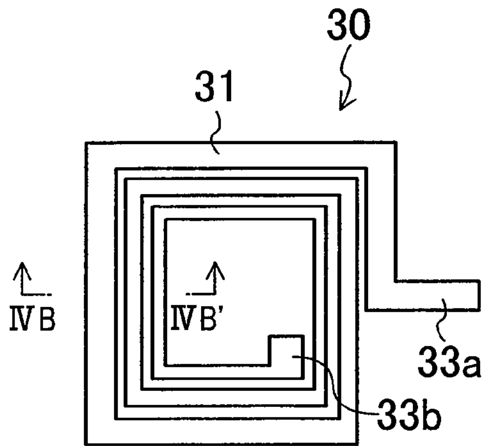


FIG.4B

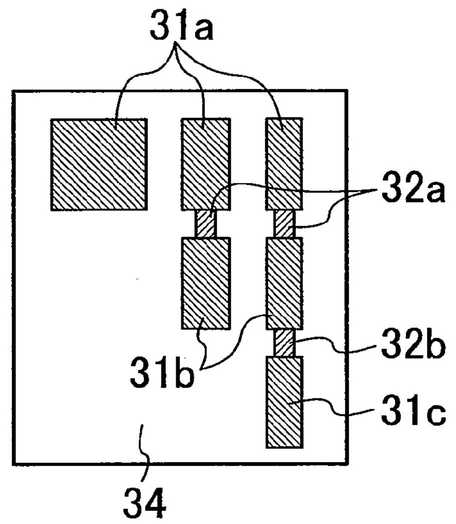


FIG.4C

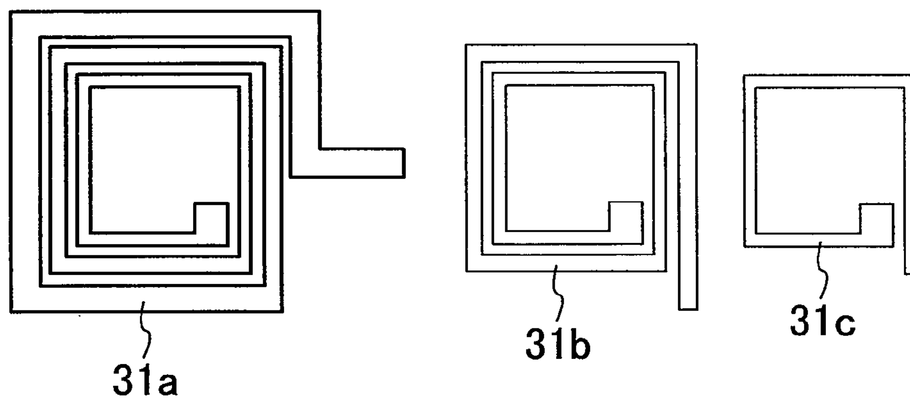


FIG.5A

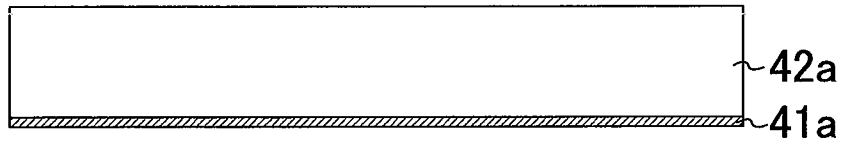


FIG.5B

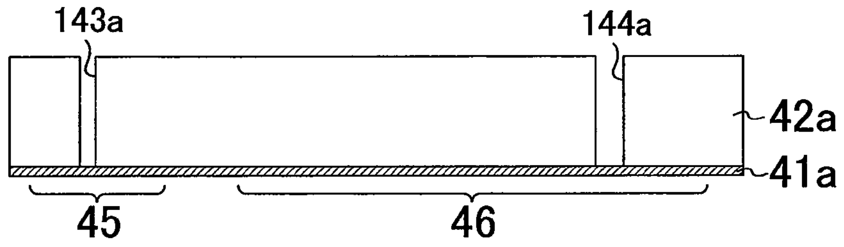


FIG.5C

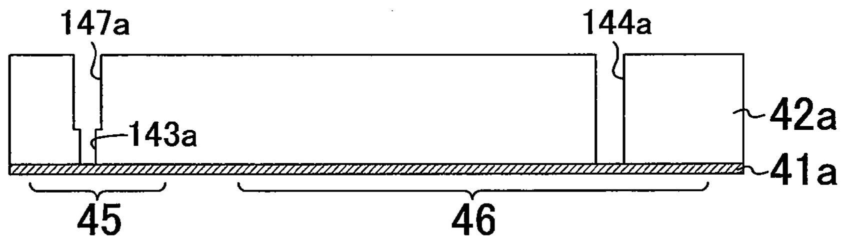


FIG.5D

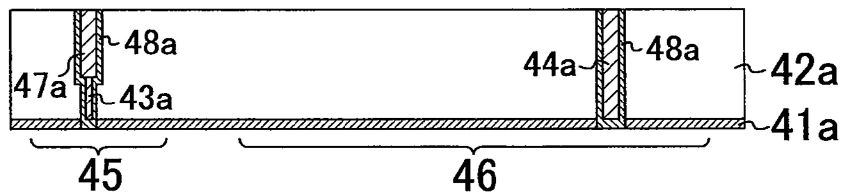


FIG.5E

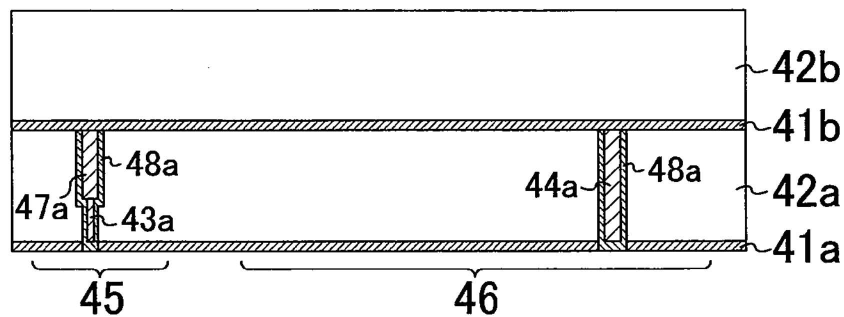


FIG.6A

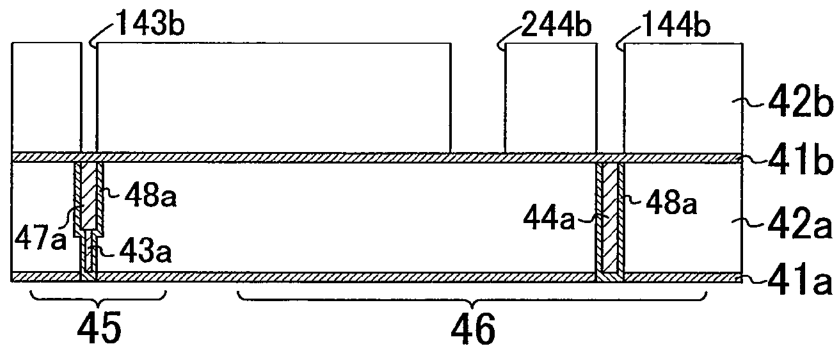


FIG.6B

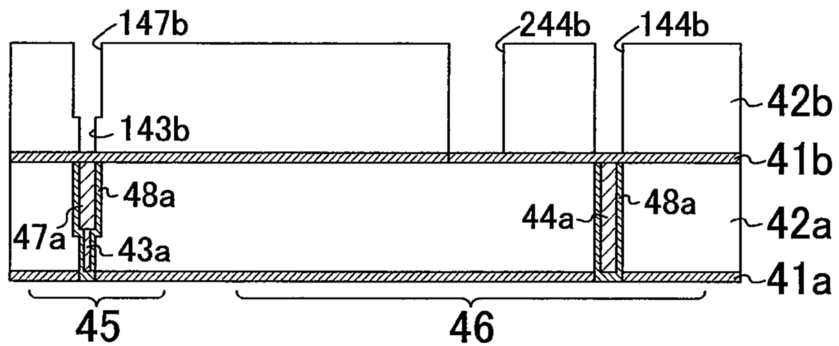


FIG.6C

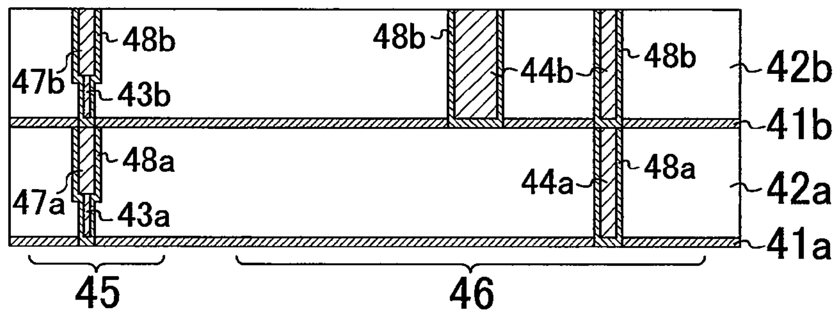


FIG.6D

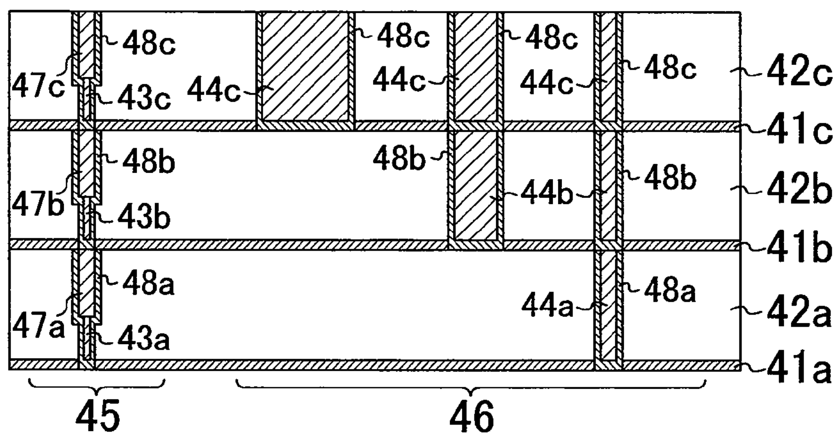


FIG.7A

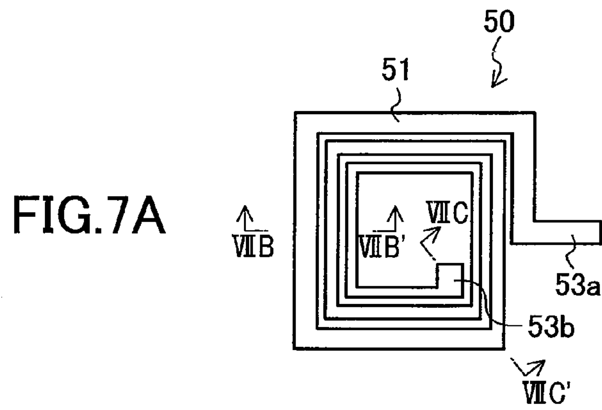


FIG.7B

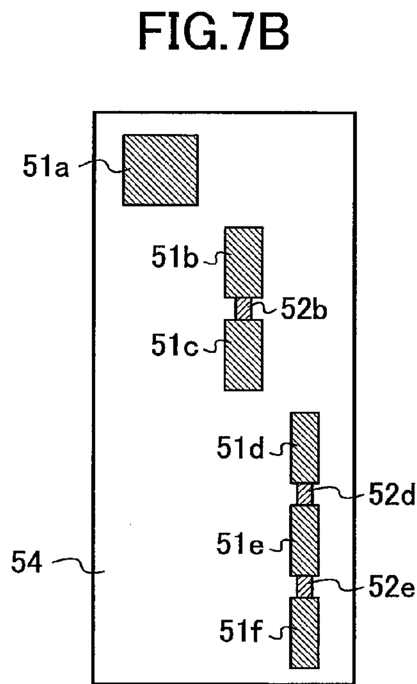


FIG.7C

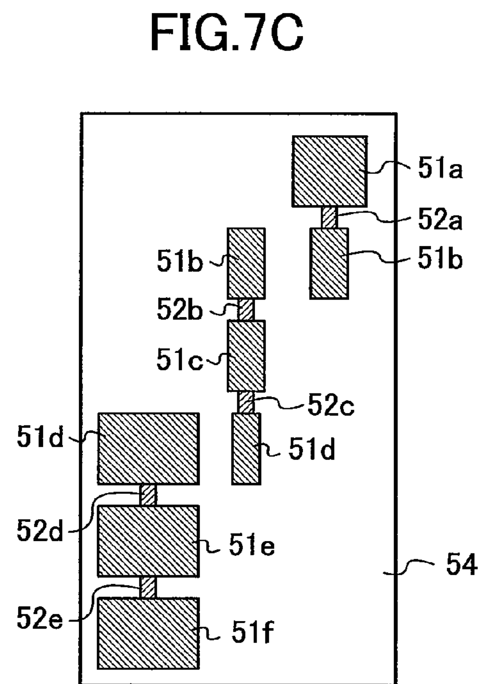


FIG.7D

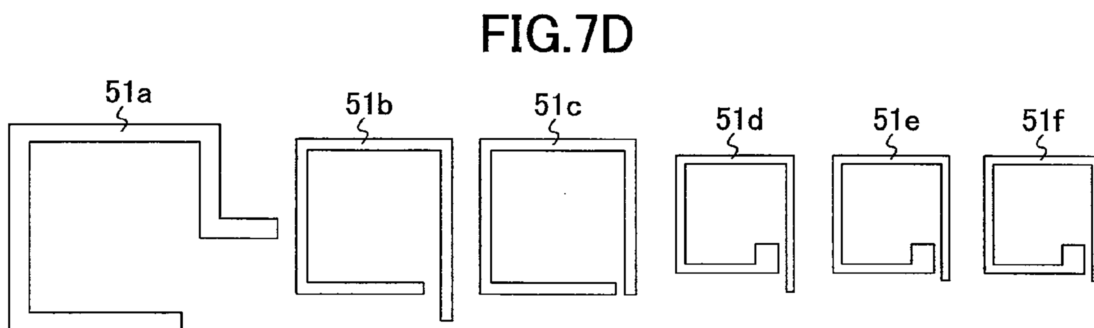


FIG.8A
PRIOR ART

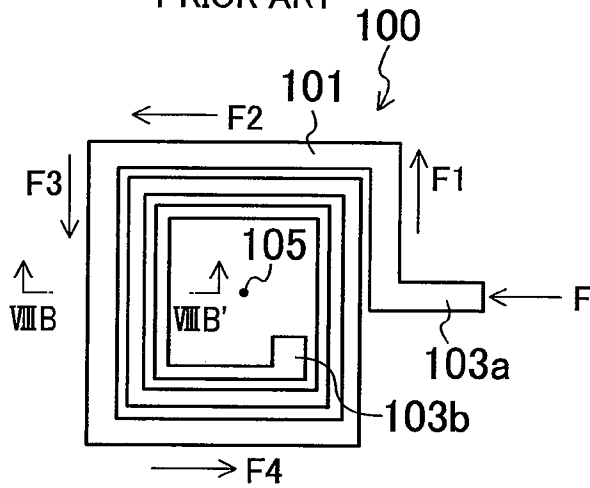


FIG.8B
PRIOR ART

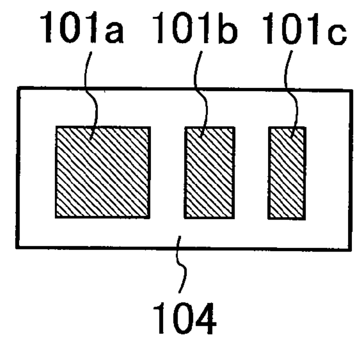
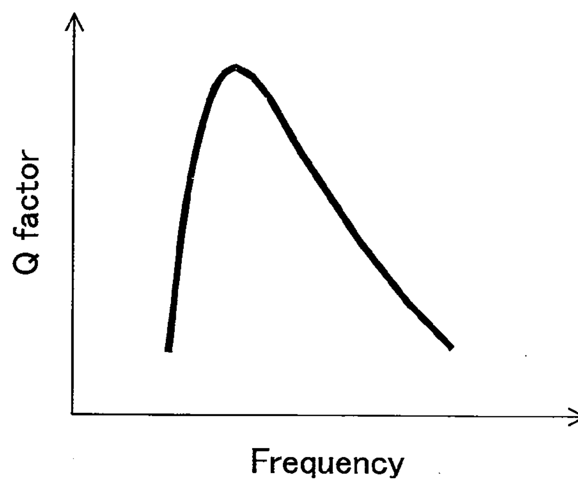


FIG.9



INDUCTOR AND METHOD FOR FABRICATING THE SAME

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority from Japanese Patent Application No. JP2008-119507 filed on May 1, 2008, which is hereby incorporated by reference in its entirety for all purposes.

BACKGROUND

The present disclosure generally relates to an inductor including a substrate and a spiral inductor formed on the substrate, and to a method for fabricating the inductor.

With recent widespread use of cellular phones and personal digital assistants (PDAs), there has been an increasing demand for reducing the size of high-frequency circuits with wireless interfaces. To meet with this demand, passive components, such as inductors, which used to be provided outside semiconductor devices, e.g., mounted on printed wiring boards (i.e., passive components which used to be external components) are housed in the semiconductor devices in many cases. Inductors are components necessary for application to the design of radio frequency integrated circuits (RFICs) such as low noise amplifiers (LNAs), power amplifiers (PAs), radio frequency (RF) oscillators. However, as compared to resistors and capacitors that are relatively easily formed within chips, inductors have various structures for acquiring inductive properties, and are not necessarily easily formed within chips.

A conventional technique (e.g., a technique disclosed in Japanese Laid-Open Patent Publication No. 2002-134319) is now described with reference to FIGS. **8**A and **8**B. FIG. **8**A is a plan view illustrating an inductor. FIG. **8**B is a cross-sectional view taken along line VIIIB-VIIIB' in FIG. **8**A.

As illustrated in FIG. **8**A, an inductor **100** has a structure where a conductor **101** is in a spiral shape. The outer and inner ends of the conductor **101** serve as a terminal **103***a* and a terminal **103***b* respectively. Current F which has entered the terminal **103***a* flows in the direction indicated by arrows F**1**, F**2**, F**3**, and F**4**, in this order, and is obtained from the terminal **103***b*.

As illustrated in FIG. **8**B, the inductor **100** (having turns **101***a*, **101***b*, and **101***c*) is provided in an interlayer insulating film **104** formed on a substrate. The conductor **101** is rectangular in a cross sectional taken along the width of the conductor **101**.

To describe characteristics of an inductor, a quality factor (Q factor) is generally used, and is expressed as:

$$Q=\omega L/R \quad (1)$$

where ω is $2\pi f$, π is a circle ratio, f is a frequency, L is an inductance, and R is a resistance.

It is considered that as the Q factor increases, electric characteristics of the inductor are enhanced. A large Q factor contributes to reduction of power consumption of a circuit.

It is well known that the series resistance of a spiral inductor is a main cause of a decrease in the Q factor of the inductor. One of measures for reducing the series resistance of the inductor is using a wide conductor. However, an increase in the width of the conductor increases the area of the inductor, thereby disadvantageously increasing parasitic capacitance relating to the structure. Consequently, the self-resonant frequency of the inductor decreases, thus limiting the effective frequency of the inductor.

In the inductor **100** illustrated in FIG. **8**A, the turns **101***a* through **101***c* of the conductor **101** are equally spaced from each other, and the inner turn **101***c* is narrower than the outer turn **101***a*. Accordingly, the distance from a center **105** to the inner turn **101***c* is larger than that in a configuration in which the inner turn **101***c* and the outer turn **101***a* have the same width. Consequently, each of opposing turns of the conductor **101** is not greatly affected by the line of magnetic force of the other turn. As a result, the inductance L increases, thus causing an increase in the Q factor.

FIG. **9** shows a Q characteristic (i.e., a variation of the Q factor with respect to the frequency) of a general inductor. As shown in FIG. **9**, as the frequency increases, the Q factor temporarily increases. However, in a high-frequency range, the Q factor decreases because of a capacitive loss due to capacitive coupling between the inductor and the substrate. As a result, the Q characteristic has a convex shape which curves upward.

According to Equation (1), to increase the Q factor, reduction of the series resistance of the inductor and suppression of the capacitive loss are effective.

SUMMARY

However, the above-described conventional configuration has the following drawbacks.

First, with an increase in the drive frequency, current tends to concentrate near the surfaces (i.e., the upper and lower surfaces and both side surfaces in the case of a configuration where a conductor is rectangular in cross section, such as turns **101***a*, **101***b*, and **101***c* in FIG. **8**B) of a conductor due to the skin effect. In addition, a magnetic field is produced in energizing an inductor. Accordingly, in a spiral conductor, there is a tendency for the magnetic flux density to be higher in an inner turn of the spiral than in an outer turn of the spiral, thus causing current to concentrate in the inner turn. When the current concentrates in the inner turn of the conductor, the substantial series resistance of the inductor increases, and thus the Q factor of the inductor decreases. To reduce the influence of the magnetic field produced during energizing operation, it will be effective to increase the distance from the center of the inductor to the conductor. Moreover, to prevent an increase in the area occupied by the inductor, measures such as reduction of the conductor width or reduction of the conductor pitch are conceivable. However, the reduction of the conductor width increases the series resistance of the inductor, resulting in a decrease in the Q factor of the inductor. The reduction of the conductor pitch increases capacitance between turns of the conductor, resulting in a decrease in the Q factor of the inductor in a high-frequency range.

To increase the Q factor of the inductor, it will be effective to increase the thickness of the conductor of the inductor. However, in the conventional inductor, the adjacent turns **101***a* and **101***b*; and **101***b* and **101***c* as shown in FIG. **8**B affect each other, and thus capacitance arises as the thickness of the turns **101***a*, **101***b*, and **101***c* increases. Consequently, the capacitance between turns of the conductor increases, thus causing a decrease in the Q factor of the inductor in a high-frequency range. Therefore, it is necessary to overcome these drawbacks.

An example inductor of this disclosure includes: a flat substrate; and a conductor in a spiral shape having a plurality of turns. The conductor is provided substantially in parallel with a principal surface of the substrate. The turns of the conductor are equally spaced from each other in a direction parallel to a plane on which the conductor is formed. An outer one of the turns of the conductor is wider and thinner than an

inner one of the turns of the conductor. A level of at least one of a top and a bottom of the conductor differs from one turn to another in a cross section vertical to the plane on which the conductor is formed.

In the spiral conductor with the structure described above, an inner turn is narrower and thicker than an outer turn, and thus the level of at least one of the top and the bottom of a turn differs from that of its adjacent turn. Accordingly, a magnetic flux component vertical to the plane on which the conductor is formed can be reduced, resulting in reduction of the total eddy current loss. That is, reduction of a component (vertical component) of magnetic flux linking the conductor can reduce the total eddy current loss, thus suppressing an increase in the substantial series resistance of the inductor. In addition, the structure in which the conductor is not uniformly thick can suppress an increase in capacitance of the inductor, thus suppressing a capacitive loss.

In the example inductor, a top of an inner one of the turns of the conductor may be flush with or below a top of an outer one of the turns of the conductor in a cross section vertical to the plane on which the conductor is formed.

Such a structure can increase the distance between adjacent turns of the spiral conductor, thus reducing the influence of a magnetic field produced in energizing the inductor, for example. In addition, a magnetic flux component vertical to the plane on which the conductor is formed can be reduced, thus reducing the total eddy current loss. As a result, an increase in the substantial series resistance can be suppressed. Furthermore, capacitance between adjacent turns of the conductor can be reduced, thus suppressing a decrease in the Q factor of the inductor in a high-frequency range.

In the example inductor, a bottom of an inner one of the turn of the conductor may be flush with or above a bottom of an outer one of the turns of the conductor in a cross section vertical to the plane on which the conductor is formed.

Such a structure can increase the distance between adjacent turns of the spiral conductor, thus reducing the influence of a magnetic field produced in energizing the inductor, for example. In addition, a magnetic flux component vertical to the plane on which the conductor is formed can be reduced, thus reducing the total eddy current loss. As a result, an increase in the substantial series resistance can be suppressed. Furthermore, capacitance between adjacent turns of the conductor can be reduced, thus suppressing a decrease in the Q factor of the inductor in a high-frequency range.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A is a plan view illustrating an inductor according to a first embodiment of the present invention. FIG. **1**B is a cross-sectional view of the inductor of the first embodiment. FIG. **1**C is a cross-sectional view of another inductor according to the first embodiment.

FIG. **2**A is a plan view illustrating an inductor according to a second embodiment of the present invention. FIG. **2**B is a cross-sectional view of the inductor of the second embodiment. FIG. **2**C is a plan view illustrating spiral shapes in respective layers of the inductor of the second embodiment.

FIG. **3**A is a cross-sectional view of another inductor according to the second embodiment. FIG. **3**B is a cross-sectional view of still another inductor of the second embodiment. FIG. **3**C is a cross-sectional view of yet another inductor of the second embodiment.

FIG. **4**A is a plan view illustrating an inductor according to a third embodiment of the present invention. FIG. **4**B is a cross-sectional view of the inductor of the third embodiment. FIG. **4**C is a plan view illustrating spiral shapes in respective layers of the inductor of the third embodiment.

FIGS. **5**A through **5**E are cross-sectional views showing process steps of a method for fabricating an inductor according to the third embodiment.

FIGS. **6**A through **6**D are cross-sectional views showing process steps of the method for fabricating an inductor according to the third embodiment.

FIG. **7**A is a plan view illustrating an inductor according to a fourth embodiment of the present invention. FIG. **7**B is a cross-sectional view of the inductor of the fourth embodiment. FIG. **7**C is another cross-sectional view of the inductor of the fourth embodiment. FIG. **7**D is a plan view illustrating spiral shapes in respective layers of the inductor of the fourth embodiment.

FIG. **8**A is a plan view illustrating a conventional inductor. FIG. **8**B is a cross-sectional view of the conventional inductor.

FIG. **9** is a graph showing a correlation between the Q factor of an inductor and a frequency.

DETAILED DESCRIPTION

Hereinafter, embodiments of the present invention will be described with reference to the drawings. The present invention is not limited to the following embodiments.

Embodiment 1

FIG. **1**A is a plan view illustrating an inductor **10** having a spiral shape according to a first embodiment of the present invention. FIG. **1**B is a cross-sectional view taken along line IB-IB' in FIG. **1**A. FIG. **1**C is another example of the cross-sectional view taken along line IB-IB' in FIG. **1**A.

As illustrated in FIG. **1**A, the inductor **10** includes a substrate (not shown) and a conductor **11** having a spiral shape. The outer and inner ends of the conductor **11** serve as a terminal **13***a* and a terminal **13***b* respectively. Current which has entered the terminal **13***a* is obtained from the terminal **13***b*. As illustrated in FIG. **1**B, the conductor **11** (only whose turns **11***a*, **11***b*, and **11***c* are shown in FIG. **1**B) is provided in an interlayer insulating film **14** formed on the substrate. Each of the turns **11***a*, **11***b*, and **11***c* is rectangular in a cross section taken along the width of the turns **11***a*, **11***b*, and **11***c*.

Referring now to FIG. **1**B, the bottom of the conductor **11** is located at different levels in different turns in this embodiment. For example, in the conductor **11** illustrated in FIG. **1**B, the bottom of the innermost turn **11***c* is located at the lowest level, the bottom of the intermediate turn **11***b* is located at an intermediate level, and the outermost turn **11***a* is located at the highest level. This structure can reduce a magnetic flux component vertical to the plane on which the conductor **11** is formed, thus reducing the total eddy current loss. That is, in the conductor **11** of this embodiment, a vertical component of magnetic flux linking the conductor **11** can be reduced, thus reducing the total eddy current loss. Consequently, the series resistance of the inductor **10** can be reduced, resulting in preventing a decrease in the Q factor of the inductor **10**.

To implement such a structure of the conductor **11**, an inner turn is made thicker than an outer turn, and the tops of these turns are flush with each other in this embodiment. Alternatively, as illustrated in FIG. **1**C, a structure in which an inner turn is thicker than an outer turn and the bottoms of these turns are flush with each other may be employed. The conductor illustrated in FIG. **1**C has the same function and advantages as those of the conductor illustrated in FIG. **1**B. Accordingly, in

the spiral conductor **11**, it is sufficient that the level of the bottom or top of the conductor **11** differs between different turns.

This embodiment is now more specifically described with reference to FIG. **1**A. The turns of the spiral conductor **11** are equally spaced from each other in the direction parallel to the plane on which the conductor **11** is formed. In such a conductor **11**, an outer turn is wider than an inner turn. For example, in the conductor **11** illustrated in FIG. **1**A, the distance between the innermost turn **11***c* and the intermediate turn **11***b* is equal to the distance between the intermediate turn **11***b* and the outermost turn **11***a*, and the width increases in the order of the innermost turn **11***c*, the intermediate turn **11***b*, and the outermost turn **11***a*.

In this conductor **11**, the distance between the center **15** of the inductor **10** and the innermost turn **11***c* is larger than that in a conductor having a uniform width. Accordingly, the conductor **11** is less affected by the vertical component of magnetic flux linking the conductor **11**. In addition, in the conductor **11**, an inner turn is narrower and thicker than an outer turn, thus suppressing an increase in the series resistance of the inductor **10** due to the reduction of the conductor width. Furthermore, in the conductor **11**, an outer turn does not need to be thicker, and thus an increase in capacitance between adjacent turns can be suppressed.

As described above, in this embodiment, the vertical component of magnetic flux linking the conductor **11** can be reduced, thus reducing the total eddy current loss. This can prevent an increase in the series resistance of the inductor **10**, resulting in suppression of a decrease in the Q factor of the inductor **10**.

In the conductor **11** of this embodiment, an inner turn is narrower and thicker than an outer turn. Accordingly, an increase in the series resistance of the inductor **10** can be suppressed, thus further suppressing a decrease in the Q factor of the inductor **10**. In addition, an increase in capacitance between adjacent turns of the conductor **11** can be suppressed, thus suppressing a decrease in the Q factor of the inductor **10** in a high-frequency range.

Embodiment 2

FIG. **2**A is a plan view illustrating an inductor **20** having a spiral shape according to a second embodiment of the present invention. FIG. **2**B is a cross-sectional view taken along line IIB-IIB' in FIG. **2**A. FIG. **2**C is a plan view illustrating spiral shapes in respective layers. FIGS. **3**A through **3**C are other examples of the cross-sectional view taken along line IIB-IIB' in FIG. **2**A.

As illustrated in FIG. **2**A, the inductor **20** includes a substrate (not shown) and a conductor **21** having a spiral shape. The outer and inner ends of the conductor **21** serve as a terminal **23***a* and a terminal **23***b* respectively. Current which has entered the terminal **23***a* is obtained from the terminal **23***b*. As illustrated in FIG. **2**B, the conductor **21** (only whose turns **21***a*, **21***b*, and **21***c* are shown in FIG. **2**B) is provided in an interlayer insulating film **24** formed on the substrate. Each of the turns **21***a*, **21***b*, and **21***c* is rectangular in a cross section taken along the width of the turns **21***a*, **21***b*, and **21***c*.

Referring now to FIG. **2**B, the bottom of the outer one of two adjacent turns is flush with the top of the inner one of the turns in this embodiment. For example, in the conductor **21** illustrated in FIG. **2**B, the bottom of the outermost turn **21***a* is flush with the top of the intermediate turn **21***b*, and the bottom of the intermediate turn **21***b* is flush with the top of the innermost turn **21***c*.

This structure allows the distance between adjacent turns of the conductor **21** of this embodiment to be larger than that of the conductor **11** of the first embodiment. Accordingly, the influence of a magnetic field produced in energizing the inductor, for example, is reduced. In addition, the levels of the top and bottom of the conductor **21** of this embodiment differ between different turns. Accordingly, as in the first embodiment, a magnetic flux component vertical to the plane on which the conductor **21** is formed can be reduced. These features can reduce the total eddy current loss, thus suppressing an increase in the series resistance of the inductor **20**. Moreover, the increase in the distance between adjacent turns of the conductor **21** reduces capacitance between adjacent turns of the conductor **21**, resulting in suppressing a decrease in the Q factor of the inductor **20** in a high-frequency range.

More specifically, in the conductor **21** of this embodiment, as illustrated in FIG. **2**B, the outermost turn **21***a* is located at the highest level, the intermediate turn **21***b* is located at an intermediate level, and the innermost turn **21***c* is located at the lowest level in the interlayer insulating film **24**. As illustrated in FIG. **2**C, the terminal **23***a* is provided at an end of the outermost turn **21***a*, and the bottom of the other end of the outermost turn **21***a* is electrically connected to the top of one end of the intermediate turn **21***b*. The bottom of the other end of the intermediate turn **21***b* is electrically connected to the top of one end of the innermost turn **21***c*, and the terminal **23***b* is provided at the other end of the innermost turn **21***c*.

As illustrated in FIG. **3**A, the top of the outer one of two adjacent turns of the conductor may be flush with the bottom of the inner one of the turns. For example, in the conductor shown in FIG. **3**A, the top of the outermost turn **21***a* is flush with the bottom of the intermediate turn **21***b*, and the top of the intermediate turn **21***b* is flush with the bottom of the innermost turn **21***c*. Even in this case, substantially the same advantages as those of the conductor **21** shown in FIG. **2**B can be obtained.

As illustrated in FIG. **3**B, the bottom of the outer one of two adjacent turns of the conductor may be located above the top of the inner one of the turns. In this case, as shown in FIG. **2**C, the terminal **23***a* is provided at an end of the outermost turn **21***a*, and the bottom of the other end of the outermost turn **21***a* is electrically connected to the top of an end of the intermediate turn **21***b* through a conductive material (not shown) provided in a via (not shown). The bottom of the other end of the intermediate turn **21***b* is electrically connected to the top of an end of the innermost turn **21***c* through a conductive material (not shown) provided in a via (not shown). The terminal **23***b* is provided at the other end of the innermost turn **21***c*. Even in this case, substantially the same advantages as those of the conductor **21** shown in FIG. **2**B can be obtained.

Moreover, as illustrated in FIG. **3**C, the top of the outer one of two adjacent turns of the conductor may be located below the bottom of the inner one of the turns. In this case, as shown in FIG. **2**C, the terminal **23***a* is provided at an end of the outermost turn **21***a*, and the top of the other end of the outermost turn **21***a* is electrically connected to the bottom of an end of the intermediate turn **21***b* through a conductive material (not shown) provided in a via (not shown). The top of the other end of the intermediate turn **21***b* is electrically connected to the bottom of an end of the innermost turn **21***c* through a conductive material (not shown) provided in a via (not shown). The terminal **23***b* is provided at the other end of the innermost turn **21***c*. Even in this case, substantially the same advantages as those of the conductor **21** shown in FIG. **2**B can be obtained.

The conductor **21** of this embodiment is now more specifically described with reference to FIG. **2**A. In the conductor **21**

of this embodiment, the turns of the conductor **21** are equally spaced from each other in the direction parallel to the plane on which the conductor **21** is formed, as in the conductor **11** of the first embodiment. In such a conductor **21**, an outer turn is wider than an inner turn. Accordingly, the conductor **21** is less affected by a vertical component of magnetic flux linking the conductor **21** than a conductor having a uniform width.

In the conductor **21** of this embodiment, an outer turn is narrower and thicker than an inner turn, as in the conductor **11** of the first embodiment. Accordingly, an increase in the series resistance of the inductor **20** can be suppressed, and thus a decrease of the Q factor of the inductor **20** can be suppressed. In addition, in this embodiment, an outer turn does not need to be thicker, as in the first embodiment. Accordingly, an increase in capacitance between adjacent turns of the conductor **21** can be suppressed. As a result, a decrease in the Q factor of the inductor **20** in a high-frequency range can be suppressed.

As described above, the conductor **21** of this embodiment not only has advantages of the conductor **11** of the first embodiment, but also allows the distance between adjacent turns of the conductor to be increased. Accordingly, an additional advantage of reduction of the influence of a magnetic field produced in energizing the inductor, for example, can be obtained.

Embodiment 3

FIG. **4**A is a plan view illustrating an inductor **30** having a spiral shape according to a third embodiment of the present invention. FIG. **4**B is a cross-sectional view taken along line IVB-IVB' in FIG. **4**A. FIG. **4**C is a plan view illustrating spiral shapes in respective layers.

As illustrated in FIG. **4**A, the inductor **30** includes a substrate (not shown) and a conductor **31** having a spiral shape. The outer and inner ends of the conductor **31** serve as a terminal **33***a* and a terminal **33***b* respectively. Current which has entered the terminal **33***a* is obtained from the terminal **33***b*. As illustrated in FIG. **4**B, the conductor **31** (only whose first-, second-, and third-layer portions **31***a*, **31***b*, **31***c* are shown in FIG. **4**B) is provided in an interlayer insulating film **34** formed on the substrate. Each of the first-through third-layer portions **31***a* through **31***c* is rectangular in a cross section taken along the width of the portions **31***a* through **31***c*.

As in the conductor **11** of the first embodiment, the turns of the spiral conductor **31** are equally spaced from each other in the direction parallel to the plane on which the conductor **31** is formed. An outer turn of the conductor **31** is wider and thinner than an inner turn of the conductor **31**. The bottom of the outer turn is located at a different level from the bottom of the inner turn. However, the specific structure of the conductor **31** is different from that of the conductor **11**.

As illustrated in FIG. **4**C, the conductor **31** includes the first-layer portion **31***a*, the second-layer portion **31***b*, and the third-layer portion **31***c*. The first-layer portion **31***a* has a spiral shape as shown in FIG. **4**C. An outer turn of this first-layer portion **31***a* is wider than, but has the same thickness as, an inner turn of the first-layer portion **31***a*.

As the first-layer portion **31***a*, the second-layer portion **31***b* also has a spiral shape. An outer turn of this second-layer portion **31***b* is wider than an inner turn of the second-layer portion **31***b*. The outermost turn of the second-layer portion **31***b* has the same width as the innermost turn of the first-layer portion **31***a*.

The third-layer portion **31***c* also has a spiral shape, and has a width equal to the width of the innermost turn of the second-layer portion **31***b*.

As shown in FIG. **4**B, the outermost turn of the conductor **31** is constituted by the outermost turn of the first-layer portion **31***a*. An intermediate turn of the conductor **31** is constituted by an intermediate turn of the first-layer portion **31***a* and the outermost turn of the second-layer portion **31***b* which are electrically connected to each other through a conductive material **32***a* provided in a via or a trench. Accordingly, the bottom of the outermost turn of the conductor **31** is located above the bottom of the intermediate turn of the conductor **31**.

In the same manner, the innermost turn of the conductor **31** is constituted by the innermost turn of the first-layer portion **31***a*, the innermost turn of the second-layer portion **31***b*, and the third-layer portion **31***c*. The innermost turn of the first-layer portion **31***a* and the innermost turn of the second-layer portion **31***b* are electrically connected to each other through a conductive material **32***a* provided in a via or a trench. The innermost turn of the second-layer portion **31***b* and the third-layer portion **31***c* are electrically connected to each other through a conductive material **32***b* provided in a via or a trench. Accordingly, the bottom of the intermediate turn of the conductor **31** is located above the bottom of the innermost turn of the conductor **31**.

It should be noted that vias or trenches are actually formed throughout the surface of the second-layer portion **31***b* to electrically connect the first-layer portion **31***a* and the second-layer portion **31***b* to each other. In the same manner, vias or trenches are formed throughout the surface of the third-layer portion **31***c* to electrically connect the second-layer portion **31***b* and the third-layer portion **31***c* to each other.

In this manner, a plurality of interconnection layers are connected to one another through conductive materials provided in vias or trenches in this embodiment. Accordingly, the inductor of this embodiment has a cross-sectional structure similar to that of the inductor of the first embodiment, and is allowed to be formed simultaneously with formation of interconnections for transistors. Then, a method for fabricating a multilayer interconnection structure according to this embodiment is described with reference to FIGS. **5**A through **5**E and FIGS. **6**A through **6**D.

First, although not shown, a semiconductor substrate (not shown) provided with, for example, a given transistor and a lower-layer interconnection is prepared, and then a SiN film as a first etch-stopper insulating film **41***a* is deposited by plasma chemical vapor deposition (CVD) to a thickness of 50 nm over the surface of an interlayer insulating film in which the lower-layer interconnection is buried. Since SiN has a higher dielectric constant than SiO_2 used as a material for the interlayer insulating film, the use of SiN as a material for the first etch-stopper insulating film **41***a* increases wire-to-wire capacitance. Hence, the thickness of the SiN film is preferably as small as possible. It should be noted that SiO_2 is a constituent of the interlayer insulating film, and therefore cannot be used as a material for the etch-stopper insulating film.

Next, a first interlayer insulating film **42***a* with a thickness of 2 μm is formed on the upper surface of the first etch-stopper insulating film **41***a* (see FIG. **5**A).

Then, after the formation of the first interlayer insulating film **42***a*, a resist mask (not shown) for forming, in the first interlayer insulating film **42***a*, a first connection portion **43***a* and a first conductor **44***a* (i.e., the third-layer portion **31***c*) for an inductor is formed on the upper surface of the first interlayer insulating film **42***a*. At this time, this resist mask includes: a circular pattern (i.e., a pattern for forming a first connection portion **43***a*) provided in an interconnection region **45**; and a linear pattern (i.e., a pattern for forming a first conductor **44***a* for an inductor) provided in an inductor region

46. In this example, the circular pattern has a diameter of 0.5 μm, and the linear pattern has a width of 0.5 μm to 10 μm.

After the formation of the resist mask on the upper surface of the first interlayer insulating film **42***a*, the first interlayer insulating film **42***a* is etched with the resist mask used as an etch mask, thereby forming a hole **143***a* for forming a first connection portion **43***a* and a trench **144***a* for forming a first conductor **44***a* (see FIG. **5**B). At this time, in the inductor region **46**, the trench **144***a* penetrates the first interlayer insulating film **42***a* in the thickness direction thereof, and thus has a depth substantially equal (i.e., 2 μm) to the thickness of the first interlayer insulating film **42***a*. In etching the first interlayer insulating film **42***a*, selective etching is employed such that the etching stops at the first etch-stopper insulating film **41***a* (i.e., the first etch-stopper insulating film **41***a* is not etched). After the etching, the resist mask is removed.

After the removal of the resist mask, a resist mask for forming a first interconnection **47***a* in the interconnection region **45** is formed on the upper surface of the first interlayer insulating film **42***a*. Then, the first interlayer insulating film **42***a* is etched with this resist mask used as an etch mask, thereby forming a trench **147***a* for forming a first interconnection **47***a* (see FIG. **5**C). The trench **147***a* for forming a first interconnection **47***a* in this interconnection region **45** has a depth of 1 μm.

After the etching, the resist mask is removed. Then, portions of the first etch-stopper insulating film **41***a* exposed at the bottom of the hole **143***a* for forming a first connection portion **43***a* in the first interlayer insulating film **42***a* and at the bottom of the trench **144***a* for forming a first conductor **44***a* in the first interlayer insulating film **42***a* are removed by etching. Thereafter, a first barrier tantalum nitride (TaN) film **48***a* with a thickness of 20 nm and a seed layer (not shown) with a thickness of 200 nm made of copper (Cu) are deposited by sputtering over the inner surface of the hole **143***a* for forming a first connection portion **43***a*, the inner surface of trench **147***a* for forming a first interconnection **47***a*, and the inner surface of the trench **144***a* for forming a first conductor **44***a*. The material for the first barrier TaN film **48***a* only needs to be conductive. In stead of TaN, titanium nitride (TiN) or tungsten nitride (WN) may be used, for example.

Subsequently, by electrolytic plating, Cu is buried in the hole **143***a* for forming a first connection portion **43***a*, the trench **147***a* for forming a first interconnection **47***a*, and the trench **144***a* for forming a first conductor **44***a*. The thickness of the buried Cu is about 2.6 μm. Then, Cu and TaN outside the hole **143***a* for forming a first connection portion **43***a*, the trench **147***a* for forming a first interconnection **47***a*, and the trench **144***a* for forming a first conductor **44***a* are removed by chemical mechanical polishing (CMP). In this manner, a first interconnection **47***a*, a first connection portion **43***a*, and a first conductor **44***a* are formed, thereby forming an interconnection structure having a cross section as illustrated in FIG. **5**D. Electroless plating is also applicable to similar formation of an interconnection layer.

Thereafter, a SiN film as a second etch-stopper insulating film **41***b* is deposited by plasma CVD to a thickness of 50 nm over the surface of the first interlayer insulating film **42***a* in which the first interconnection **47***a*, the first connection portion **43***a*, and the first conductor **44***a* are buried. A second interlayer insulating film **42***b* with a thickness of 2 μm is then formed on the second etch-stopper insulating film **41***b* (see FIG. **5**E).

After the formation of the second interlayer insulating film **42***b*, a resist mask for forming, in the second interlayer insulating film **42***b*, a second connection portion **43***b* and a second conductor **44***b* (i.e., the second-layer portion **31***b*) for an inductor is formed on the upper surface of the second interlayer insulating film **42***b*. This resist mask includes: a circular pattern (i.e., a pattern for forming a second connection portion **43***b*) provided in the interconnection region **45**; and a linear pattern (i.e., a pattern for forming a second conductor **44***b* for an inductor) provided in the inductor region **46**. In this example, the circular pattern has a diameter of 0.5 μm, and the linear pattern has a width of 0.5 μm to 10 μm. The linear pattern is composed of two types of patterns having different widths: a narrow pattern and a wide pattern. The narrow pattern is preferably located directly above the first conductor **44***a*. The wide pattern is preferably located at an outer side (i.e., closer to the periphery) than the narrow pattern.

After the formation of the resist mask on the upper surface of the second interlayer insulating film **42***b*, the second interlayer insulating film **42***b* is etched with the resist mask used as an etch mask, thereby forming a hole **143***b* for forming a second connection portion **43***b* and trenches **144***b* and **244***b* for forming second conductors **44***b* in the second interlayer insulating film **42***b* (see FIG. **6**A). At this time, in the inductor region **46**, the trenches **144***b* and **244***b* penetrate the second interlayer insulating film **42***b* in the thickness direction thereof, and thus have a depth substantially equal (i.e., 2 μm) to the thickness of the second interlayer insulating film **42***b*. In etching the second interlayer insulating film **42***b*, selective etching is employed such that the etching stops at the second etch-stopper insulating film **41***b* (i.e., the second etch-stopper insulating film **41***b* is not etched). With this etching, two trenches **144***b* and **244***b* for forming second conductors **44***b* are formed in the second interlayer insulating film **42***b*. The two trenches **144***b* and **244***b* have different widths. The narrow trench **144***b* is located directly above the first conductor **44***a*. The wide trench **244***b* is located at an outer side (i.e., closer to the periphery) than the narrow trench **144***b*.

After the etching, the resist mask is removed. Then, a resist mask for forming a second interconnection **47***b* in the interconnection region **45** is formed on the upper surface of the second interlayer insulating film **42***b*. Thereafter, the second interlayer insulating film **42***b* is etched with the resist mask used as an etch mask, thereby forming a trench **147***b* for forming a second interconnection **47***b* (see FIG. **6**B). The trench **147***b* for forming a second interconnection **47***b* in the interconnection region **45** has a depth of 1 μm. After the etching, the resist mask is removed. Then, portions of the second etch-stopper insulating film **41***b* exposed at the bottom of the hole **143***b* for forming a second connection portion **43***b* in the second interlayer insulating film **42***b* and at the bottoms of the trenches **144***b* and **244***b* for forming second conductors **44***b* in the second interlayer insulating film **42***b* are removed by etching.

Subsequently, a second barrier TaN film **48***b* is deposited by sputtering to a thickness of 20 nm over the inner surface of the hole **143***b* for forming a second connection portion **43***b*, the inner surface of the trench **147***b* for forming a second interconnection **47***b*, and the inner surfaces of the trenches **144***b* and **244***b* for forming second conductors **44***b*. On the second barrier TaN film **48***b*, a seed layer (not shown) made of Cu and having a thickness of 200 nm is formed. As in the case of the first barrier TaN film **48***a*, the second barrier TaN film **48***b* only needs to be made of a conductive material.

Then, by electrolytic plating, Cu is buried in the hole **143***b* for forming a second connection portion **43***b*, the trench **147***b* for forming a second interconnection **47***b*, and the trenches **144***b* and **244***b* for forming second conductors **44***b*. The thickness of the buried Cu is about 2.6 μm. Then, Cu and TaN outside the hole **143***b* for forming a second connection portion **43***b*, the trench **147***a* for forming a second interconnec-

tion **47**_b_, and the trenches **144**_b_ and **244**_b_ for forming second conductors **44**_b_ are removed by CMP. In this manner, a second interconnection **47**_b_, a second connection portion **43**_b_, and second conductors **44**_b_ are formed, thereby forming a multilayer interconnection structure having a cross section as illustrated in FIG. **6**C.

Thereafter, a SiN film as a third etch-stopper insulating film **41**_c_ is deposited by plasma CVD to a thickness of 50 nm over the surface of the second interlayer insulating film **42**_b_ in which the second interconnection **47**_b_, the second connection portion **43**_b_, and the second conductors **44**_b_ are buried. A third interlayer insulating film **42**_c_ with a thickness of 2 μm is then formed on the third etch-stopper insulating film **41**_c_. Thereafter, a resist mask for forming a third connection portion **43**_c_ and a third conductor **44**_c_ (i.e., the first-layer portion **31**_a_) is formed on the upper surface of the third interlayer insulating film **42**_c_. This resist mask includes: a circular pattern (i.e., a pattern for forming a third connection portion **43**_c_) provided in the interconnection region **45**; and a linear pattern (i.e., a pattern for forming a third conductor **44**_c_) provided in the inductor region **46**. In this example, the circular pattern has a diameter of 0.5 μm, and the linear pattern has a width of 0.5 μm to 10 μm. The linear pattern is composed of three types of patterns having different widths: a first-narrowest pattern (which is the narrowest of the three types of patterns); a second-narrowest pattern; and a third-narrowest pattern. The first-narrowest pattern is preferably located directly above the narrower one of the second conductors **44**_b_. The second-narrowest pattern is preferably located directly above the wider one of the second conductors **44**_b_. The third-narrowest pattern is located at an outer side (i.e., closer to the periphery) than the second-narrowest pattern.

The third interlayer insulating film **42**_c_ is etched with the resist mask used as an etch mask, thereby forming a hole (not shown) for forming a third connection portion **43**_c_ and trenches (not shown) for forming third conductors **44**_c_ for an inductor in the third interlayer insulating film **42**_c_. At this time, in the inductor region **46**, the trenches penetrate the third interlayer insulating film **42**_c_ in the thickness direction thereof, and thus has a depth substantially equal (i.e., 2 μm) to the thickness of the third interlayer insulating film **42**_c_. In etching the third interlayer insulating film **42**_c_, selective etching is employed such that the etching stops at the third etch-stopper insulating film **41**_c_ (i.e., the third etch-stopper insulating film **41**_c_ is not etched). With this etching, three trenches for forming third conductors **44**_c_ for an inductor are formed in the third interlayer insulating film **42**_c_. These three trenches have different widths. The first-narrowest trench (which is the narrowest of the three trenches) is located directly above the narrower one of the second conductors **44**_b_. The second-narrowest trench is located directly above the wider one of the second conductors **44**_b_. The third-narrowest trench is located at an outer side (i.e., closer to the periphery) than the second-narrowest trench.

After the etching, the resist mask is removed. Then, a resist mask for forming a third interconnection **47**_c_ in the interconnection region **45** is formed on the upper surface of the third interlayer insulating film **42**_c_. The third interlayer insulating film **42**_c_ is etched with this resist mask used as an etch mask, thereby forming a trench (not shown) for forming a third interconnection **47**_c_. The trench for forming a third interconnection **47**_c_ in the interconnection region **45** has a depth of 1 μm. After the etching, the resist mask is removed. Then, portions of the third etch-stopper insulating film **41**_c_ exposed at the bottom of the hole for forming a third connection portion **43**_c_ in the third interlayer insulating film **42**_c_ and at the bottoms of the trenches for forming third conductors **44**_c_ in the third interlayer insulating film **42**_c_ are removed by etching.

Thereafter, a third barrier TaN film **48**_c_ is deposited by sputtering to a thickness of 20 nm over the inner surface of the hole for forming a third connection portion **43**_c_, the inner surface of the trench for forming a third interconnection **47**_c_, and the inner surfaces of the trenches for forming third conductors **44**_c_. On the third barrier TaN film **48**_c_, a seed layer (not shown) made of Cu and having a thickness of 200 nm is formed. As in the case of the second barrier TaN film **48**_b_, the third barrier TaN film **48**_c_ only needs to be made of a conductive material.

Then, by electrolytic plating, Cu is buried in the hole for forming a third connection portion **43**_c_, and the trench for forming a third interconnection **47**_c_, and the trenches for forming third conductors **44**_c_. The thickness of the buried Cu is about 2.6 μm. Then, Cu and TaN outside the hole for forming a third connection portion **43**_c_, the trench for forming a third interconnection **47**_c_, and the trenches for forming third conductors **44**_c_ are removed by CMP. In this manner, a third interconnection **47**_c_, a third connection portion **43**_c_, and third conductors **44**_c_ are formed, thereby forming a multilayer interconnection structure having a cross section as illustrated in FIG. **6**D.

In this manner, in this embodiment, the level of the bottom of the conductor **31** differs between different turns. Accordingly, as in the first embodiment, a magnetic flux component vertical to the plane on which the conductor **31** is formed can be reduced. Consequently, the total eddy current loss can be reduced, thus suppressing an increase in the substantial series resistance of the inductor **30**. In addition, an increase in capacitance between adjacent turns of the conductor **31** can be suppressed, resulting in suppressing a decrease in the Q factor of the inductor **30** in a high-frequency range.

As illustrated in FIG. **1**C, the level of the top of the conductor **31** may differ between different turns. Even in such a case, advantages similar to those of this embodiment can be achieved.

Embodiment 4

FIG. **7**A is a plan view illustrating an inductor **50** having a spiral shape according to a fourth embodiment of the present invention. FIG. **7**B is a cross-sectional view taken along line VIIB-VIIB' in FIG. **7**A. FIG. **7**C is a cross-sectional view taken along line VIIC-VIIC' in FIG. **7**A. FIG. **7**D is a plan view illustrating spiral shapes in respective layers.

As illustrated in FIG. **7**A, the inductor **50** includes a substrate (not shown) and a conductor **51** having a spiral shape. The outer and inner ends of the conductor **51** serve as a terminal **53**_a_ and a terminal **53**_b_ respectively. Current which has entered the terminal **53**_a_ is obtained from the terminal **53**_b_. As illustrated in FIG. **7**B, the conductor **51** (only whose first-, second-, third-, fourth-, fifth-, and sixth-layer portions **51**_a_, **51**_b_, **51**_c_, **51**_d_, **51**_e_, and **51**_f_ are shown in FIG. **7**B) is provided in an interlayer insulating film **54** formed on the substrate. Each of the first- through sixth-layer portions **51**_a_ through **51**_f_ is rectangular in a cross section taken along the width of the portions **51**_a_, for example.

As in the conductor **21** of the second embodiment, the turns of the spiral conductor **51** are equally spaced from each other in the direction parallel to the plane on which the conductor **51** is formed. An outer turn of the conductor **51** is wider and thinner than an inner turn of the conductor **51**. The top and bottom of the outer turn are respectively located at different

levels from those of the inner turn. However, the specific structure of the conductor **51** is different from that of the conductor **21**.

The conductor **51** includes the first-layer portion **51***a*, the second-layer portion **51***b*, the third-layer portion **51***c*, the fourth-layer portion **51***d*, the fifth-layer portion **51***e*, and the sixth-layer portion **51***f*. Each of these portions has a spiral shape. With respect to the width, the first-layer portion **51***a* is the widest of these conductor portions, the second-layer portion **51***b* and the third-layer portion **51***c* have an identical width, the fourth-layer portion **51***d*, the fifth-layer portion **51***e*, and the sixth-layer portion **51***f* have an identical width and are the narrowest.

In the interlayer insulating film **54**, the first-layer portion **51***a*, the second-layer portion **51***b*, the third-layer portion **51***c*, the fourth-layer portion **51***d*, the fifth-layer portion **51***e*, and the sixth-layer portion **51***f* are arranged in this order from the top to the bottom of the interlayer insulating film **54**. The first-layer portion **51***a* constitutes the outermost turn of the conductor **51**. The second-layer portion **51***b* and the third-layer portion **51***c* constitute the intermediate turn of the conductor **51**. The fourth-layer portion **51***d*, the fifth-layer portion **51***e*, and the sixth-layer portion **51***f* constitute the innermost turn of the conductor **51**.

Specifically, as illustrated in FIG. **7**A, the terminal **53***a* is provided at an end of the first-layer portion **51***a*. The other end of the first-layer portion **51***a* is electrically connected to an end of the second-layer portion **51***b* through a conductive material **52***a* provided in a via or a trench, as illustrated in FIG. **7**C. As illustrated in FIGS. **7**B and **7**C, the second-layer portion **51***b* and the third-layer portion **51***c* are connected to each other through conductive materials **52***b* provided in a large number of vias or trenches. The vias or trenches are actually formed throughout the surface of the third-layer portion **51***c*.

As illustrated in FIG. **7**C, an end of the third-layer portion **51***c* is connected to an end of the fourth-layer portion **51***d* through a conductive material **52***c* provided in a via or a trench. As illustrated in FIGS. **7**B and **7**C, the fourth-layer portion **51***d* and the fifth-layer portion **51***e* are connected to each other through conductive materials **52***d* provided in a large number of vias or trenches. The vias and trenches are actually formed throughout the surface of the fifth-layer portion **51***e*. The fifth-layer portion **51***e* and the sixth-layer portion **51***f* are connected to each other through conductive materials **52***e* provided in a large number of vias or trenches. The vias and trenches are actually formed throughout the surface of the sixth-layer portion **51***f*.

In this manner, in the conductor **51** of this embodiment, the bottom of the outermost first-layer portion **51***a* is located above the top of the intermediate second-layer portion **51***b*, and the bottom of the intermediate third-layer portion **51***c* is located above the top of the innermost fourth-layer portion **51***d*, for example. Accordingly, the inductor of this embodiment has a cross-sectional structure similar to that of the inductor of the second embodiment, and thus the same advantages as those of the second embodiment can be achieved. In other words, in this embodiment, the distance between adjacent turns of the conductor can be increased, thus reducing the influence of a magnetic field produced in energizing the inductor, for example. In addition, in the conductor **51** of this embodiment, the levels of the top and bottom of the conductor differ between different turns. Accordingly, a magnetic flux component vertical to the plane on which the conductor **51** is formed can be reduced, as in the second embodiment. These features can reduce the total eddy current loss, thus suppressing an increase in the series resistance of the inductor **50**. Moreover, as in the second embodiment, capacitance between adjacent turns of the conductor **51** can be reduced, resulting in suppressing a decrease in the Q factor of the inductor **50** in a high-frequency range.

To fabricate the multilayer interconnection structure of this embodiment, the method for fabricating a multilayer interconnection structure according to the third embodiment may be employed.

In the foregoing first through fourth embodiments, the inductor has a quadrilateral spiral shape. However, the spiral shape is not limited to quadrilaterals, and may be triangles, five or more sided polygons (i.e., pentagons, hexagon, and so forth), or circles.

In the third and fourth embodiments, a dual damascene process is employed in the fabrication method. However, the dual damascene process is not necessarily employed, and other processes may be employed.

In addition, the number of interconnection layers or turns of a spiral may be different from those described in the embodiments. As a conductive material for the conductor, materials such as Al may be used. To connect portions of the conductor, other conductive materials such as W may be used.

In the first through fourth embodiments, various modifications and changes may be made without departing from the scope of the invention as set forth in the claims below.

What is claimed is:

1. An inductor, comprising:

a flat substrate; and

a conductor in a spiral shape having a plurality of turns, wherein

the conductor is provided substantially in parallel with a principal surface of the substrate,

the turns of the conductor are equally spaced from each other in a direction parallel to a plane on which the conductor is formed,

an outer one of the turns of the conductor is wider and thinner than an inner one of the turns of the conductor, and

a level of at least one of a top and a bottom of the conductor differs from one turn to another in a cross section vertical to the plane on which the conductor is formed.

2. The inductor of claim **1**, wherein a top of an inner one of the turns of the conductor is flush with or below a top of an outer one of the turns of the conductor in a cross section vertical to the plane on which the conductor is formed.

3. The inductor of claim **1**, wherein a bottom of an inner one of the turn of the conductor is flush with or above a bottom of an outer one of the turns of the conductor in a cross section vertical to the plane on which the conductor is formed.

4. The inductor of claim **1**, wherein a plurality of interconnection layers are stacked on the principal surface of the substrate with an insulating film sandwiched between each adjacent ones of the interconnection layers, and

portions of the conductor respectively provided in at least two opposing ones of the interconnection layers are connected to each other through a conductive material provided in one of a via and a trench formed in the insulating film.

5. A method for fabricating an inductor including a flat substrate and a conductor in a spiral shape having a plurality of turns, the method comprising:

forming a first trench through a first interlayer insulating film provided on the substrate, and forming a first portion of the conductor in the first trench;

forming a second interlayer insulating film at a selected one of an upper surface and a lower surface of the first interlayer insulating film with an etch-stopper insulating

film sandwiched between the first interlayer insulating film and the second interlayer insulating film; and

forming second and third trenches through the second interlayer insulating film, and forming second and third portions of the conductor in the second and third trenches respectively, wherein

the second trench has the same width as the first trench, and reaches a surface of the first portion of the conductor at the selected one of the upper and lower surfaces of the first interlayer insulating film, and

the third trench is wider than the second trench, and is located closer to a periphery of the selected one of the upper and lower surfaces of the first interlayer insulating film than the second trench.

6. An inductor, comprising:

a substrate; and

a spiral shape conductor having a plurality of turns, wherein

the spiral shape conductor is provided substantially in parallel with a principal surface of the substrate,

the plurality of turns of the spiral shape conductor are equally spaced from each other in a direction parallel to a plane on which the spiral shape conductor is formed,

an outer one of the plurality of turns of the spiral shape conductor is wider and thinner than an inner one of the plurality of turns of the spiral shape conductor, and

a level of at least one of a top and a bottom of the spiral shape conductor differs from one turn to another in a cross section vertical to the plane on which the spiral shape conductor is formed.

7. The inductor of claim **6**, wherein a top of an inner one of the plurality of turns of the spiral shape conductor is flush with or below a top of an outer one of the plurality of turns of the spiral shape conductor in a cross section vertical to the plane on which the spiral shape conductor is formed.

8. The inductor of claim **6**, wherein a bottom of an inner one of the plurality of turns of the spiral shape conductor is flush with or above a bottom of an outer one of the plurality of turns of the spiral shape conductor in a cross section vertical to the plane on which the spiral shape conductor is formed.

9. The inductor of claim **6**, wherein a plurality of interconnection layers are stacked on the principal surface of the substrate with an insulating film sandwiched between each adjacent ones of the interconnection layers, and portions of the spiral shape conductor respectively provided in at least two opposing ones

of the interconnection layers are connected to each other through a conductive material provided in one of a via and a trench formed in the insulating film.

10. A method for fabricating an inductor including a substrate and a spiral shape conductor having a plurality of turns, the method comprising:

forming a first trench through a first interlayer insulating film provided on the substrate, and forming a first portion of the spiral shape conductor in the first trench;

forming a second interlayer insulating film at a surface of the first interlayer insulating film with an etch-stopper insulating film sandwiched between the first interlayer insulating film and the second interlayer insulating film; and

forming second and third trenches through the second interlayer insulating film, and forming second and third portions of the spiral shape conductor in the second and third trenches respectively, wherein

the second trench reaches a surface of the first portion of the spiral shape conductor at the surface of the first interlayer insulating film, and

the third trench is wider than the second trench.

11. A method for fabricating an inductor including of claim **10**, wherein the second trench has the same width as the first trench.

12. A method for fabricating an inductor including of claim **10**, wherein the third trench is located at the outer of the plurality of the turns, and

the second trench is located at the inner of the plurality of the turns.

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